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EXPERIMENTAL VERIFICATION OF KINEMATIC MODEL OF SCORBOT ER-4U ROBOT MANIPULATOR

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ABSTRACT

Kinematic modelling of a robot is important for developing position control algorithms for the robots. This paper features the kinematic modeling of a 5-axis SCORBOT ER 4u stationary articulated robot arm. A mathematical kinematic model was developed based on D-H parameters. The kinematic model was validated experimentally, by comparing reference and measured wrist positions in the Cartesian space.

KEYWORDS: Robot Manipulator, Kinematics & D-H Parameters

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Original Article

INTRODUCTION

"Robot manipulator" is defined as a chain of links and joints. One end is connected to ground, and at the free end is attached an end effector or gripping device. It is assumed that a link is a rigid body [1]. The problem of kinematics is to describe the motion of the manipulator without consideration of the forces and torques causing the motion.

Robot Kinematics

There are two different ways to express the position of any link: using the *Cartesian* space, which consists of position (x, y, z), or using the joint space, by representing the position by the angles of the manipulator's links[2]. Forward kinematics is the transformation from joint space to Cartesian spacei.e.to determine the position and orientation of the end-effectors given the values for the joint variables of the robot.It is used to describe the static position and orientation of the manipulator linkages.The transformation of the position and orientation of a robot’s end-effector from Cartesian space to joint space is termed as inverse kinematics.Transformations depends on the configuration of the robot i.e., type of each joint, link lengths, joint positions etc.).

Scorbot ER-4u

The SCORBOT-ER 4u [3] is a vertical articulated robot, with five revolute joints as shown in figure 1. With gripper attached, the robot has six degrees of freedom. This design permits the end effector to be positioned and oriented arbitrarily within a large work space.

The Tool Center Point (TCP) of robot is at the center of the gripper pads. The origin of the coordinate system is at the center of the robot base at table level. A robot position in Joint coordinates is defined by Base, Shoulder, Elbow, Pitch and Roll angle.

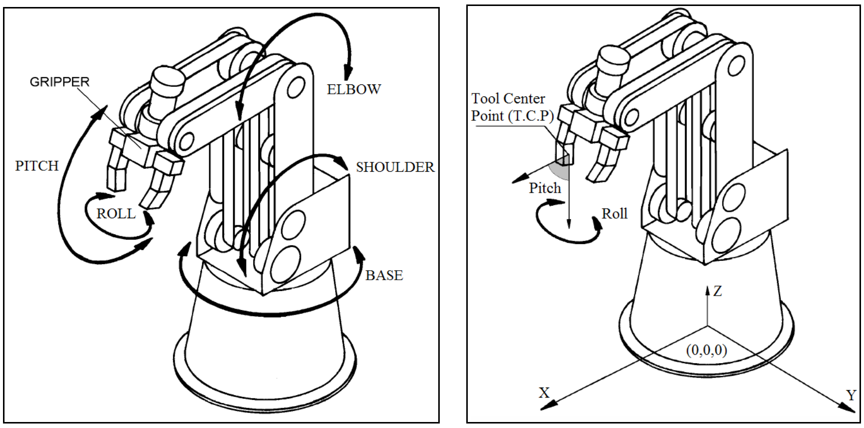

Figure 1: SCORBOT-ER 4u Configuration

A robot position in Cartesian (or XYZ) coordinates is defined by the distance of the robots Tool Center Point (TCP) from the point of origin (the center bottom of the robot base), along the three axes and the Pitch (P) and Roll (R) angles of the gripper, specified in angular units.

The robot is supported by RoboCell 3D graphic software used to design, create and control simulated industrial workcells. RoboCell (Figure 2) fully integrated with SCORBASE robotics programming and control software.

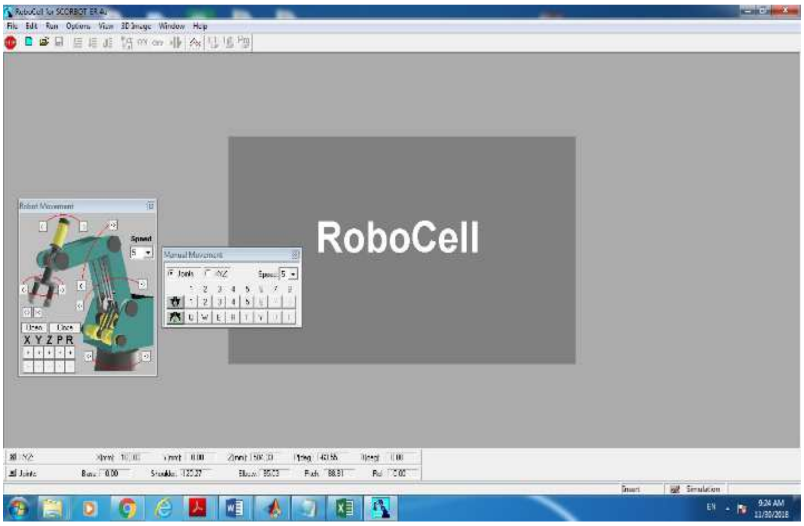

Figure 2: Robocell Interface for SCORBOT-ER 4u

OBJECTIVE

The objective of the paper is to model the forward and inverse kinematics of SCORBOT-ER 4u and validate the kinematic model, experimentally.

KINEMATIC MODEL OF SCORBOT ER-4U ROBOT

Kinematic modeling of robots requires attaching reference frames to the links of the robot. In the present work Denavit-Hartenberg notation, which is a popular and reliable approach for attaching reference frames to spatial kinematic chain links, is used for kinematic modeling of the SCORBOT-ER 4u robotic manipulator.

Denavit-Hartenberg Notation

In order to describe the location of each link relative to its neighbor, a frame is attached to each link, and then a set of parameters is specified that characterized this frame, as shown in figure 3. This representation is called the *Denavit-Hartenberg* notation [2] discussed in following section.

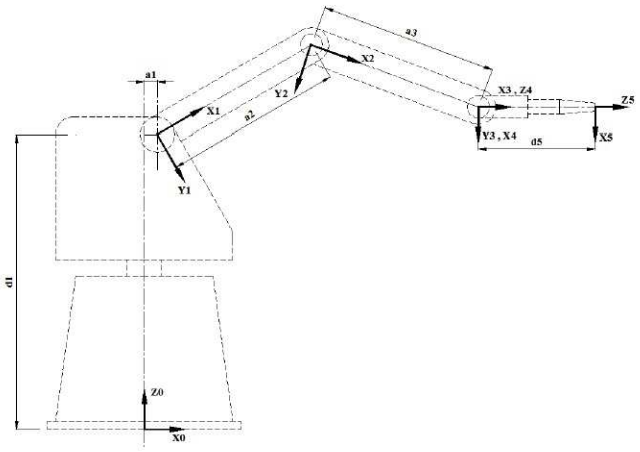

Figure 3: Frame Assignment to Each Joint

In this convention, each homogeneous transformation is represented as a product of four basic transformations. The four quantities θ_i, a_i, d_i, α_i are parameters associated with link *i* and joint *i*. These four parameters θ_i, a_i, d_i and α_i are generally given the names link length, link twist, link offset, and joint angle, respectively. These parameters of Scorbot ER 4-u [4][5][7] are given in the Table 1.

Table 1: D-H Parameter for SCORBOT ER-4u

Joint $_i$	a_i	d_i	α_i	θ_i	Range
1	16	349	$-\pi/2$	θ_1	-155° to 155°
2	221	0	0	θ_2	-35° to 130°
3	221	0	0	θ_3	130° to -130°
4	0	0	$\pi/2$	$\theta_4 + \pi/2$	130° to -130°
5	0	145	0	θ_5	-570° to 570°

Forward Kinematics

The transformation matrix [5], [6], [7], [8] was obtained on the following rotation/translation axis:

- A rotation about z_i axis by an angle θ_i
- Translation along z_{i-1} axis by distance d_i
- Translation by distance a_i along x_i
- Rotation by angle α_i about x_i axis

$${}^{i-1}T_i = T_z(\theta_i)T_z(d_i)T_x(a_i)T_x(\alpha_i)$$

$$ {}^{i-1}T_i = \begin{bmatrix} C\theta_i & -S\theta_i & 0 & 0 \\ S\theta_i & C\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C\alpha_i & -S\alpha_i & 0 \\ 0 & S\alpha_i & C\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{i-1}T_i = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\theta_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

where $S\theta_i=\sin(\theta_i)$ $C\theta_i=\cos(\theta i)$, $S\alpha_i=\sin(\alpha_i)$,

$C\alpha_i=\cos(\alpha_i)$, $S_{ijk}=\sin(\theta_i+\theta_j+\theta_k)$, $C_{ijk}=\sin(\theta_i+\theta_j+\theta_k)$

The overall transformation matrix, ${}^0T_5={}^0T_1\,{}^1T_2\,{}^2T_3\,{}^3T_4\,{}^4T_5$

$$ {}^0T_1 = \begin{bmatrix} C_1 & 0 & -S_1 & a_1C_1 \\ S_1 & 0 & C_1 & a_1S_1 \\ 0 & -1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \; {}^1T_2 = \begin{bmatrix} C_2 & -S_1 & 0 & a_2C_2 \\ S_2 & C_2 & 0 & a_2S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \; {}^2T_3 = \begin{bmatrix} C_3 & -S_3 & 0 & a_3C_3 \\ S_3 & C_3 & 0 & a_3S_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \; {}^3T_4 = \begin{bmatrix} -S_4 & 0 & C_4 & 0 \\ C_4 & 0 & S_4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \; {}^4T_5 = \begin{bmatrix} C_5 & -S_5 & 0 & 0 \\ S_5 & C_5 & 0 & 0 \\ 0 & 0 & 1 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Therefore the overall transformation matrix T= ${}^0T_5$

$$ T={}^0T_5 = \begin{bmatrix} -C_1C_5S_{234}-S_1S_5 & -S_1C_5+C_1S_5S_{234} & C_1C_{234} & C_1(a_1+a_2C_2+a_3C_{23}+d_5C_{234} \\ C_1S_5-S_1C_5S_{234} & C_1C_5+S_1S_5S_{234} & S_1C_{234} & S_1(a_1+a_2C_2+a_3C_{23}+d_5C_{234} \\ -C_5C_{234} & S_5C_{234} & -S_{234} & (d_1-a_2S_2-a_3S_{23}-d_5S_{234}) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

The value of X, Y, Zi.e the Tool Center Point found from last column of transformation matrix as: -

$$ X = C_1(a_1+a_2C_2+a_3C_{23}+d_5C_{234}) \tag{2} $$

$$ Y = S_1(a_1+a_2C_2+a_3C_{23}+d_5C_{234}) \tag{3} $$

$$ Z = (d_1-a_2S_2-a_3S_{23}-d_5S_{234}) \tag{4} $$

Pitch: Pitch (figure 4) is the angle of rotation about Y_5 axis of end-effector. It was obtained as the summation of all previous joint angles.

$$ Pitch\ \beta = (\theta_2+\theta_3+\theta_4) = \theta_{234} \tag{5} $$

Inverse Kinematics

Tasks to be performed by a manipulator are in the Cartesian space, whereas actuators work in joint space. Cartesian space includes position vector and orientation matrix. However, joint space is described by joint angles [2].

The transformation of the position and orientation of a robot's end-effector from Cartesian space to joint space is termed as inverse kinematics. The equations of joint variables in terms of position and orientation of the end-effector was to be formulated. There are three methods namely, geometric, algebraic [7] and Iterative solution [4] used for deriving the inverse kinematics solution [4].

For SCORBOT, Cartesian space is defined by five parameter i.e x, y, z, roll (β), *pitch* (γ) [8],[11],[12],. For joint parameter evaluation, transformation matrix is constructed from five parameters in Cartesian coordinate space. For that, rotation matrix is generated which depends on only *roll, pitch and yaw* of robotic arm.

So, the total transformation matrix is as follows:-

$$T = \begin{bmatrix} -S_\beta S_\alpha - C_\alpha C_\beta S_\gamma & -S_\beta C_\alpha + S_\alpha C_\beta S_\gamma & C_\beta C_\gamma & X \\ C_\beta S_\alpha - C_\alpha S_\beta S_\gamma & C_\beta C_\alpha + S_\beta S_\gamma S_\alpha & C_\gamma S_\beta & Y \\ -C_\alpha C_\gamma & C_\gamma S_\alpha & -S_\gamma & Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

After comparing the transformation matrix (1) with (6), it can be deduced that

$\theta_1 = \alpha$,

$\theta_{234} = \beta$,

$\theta_5 = \gamma$

So, the calculation of *yaw* is as follow: -

$$\alpha = \theta_1 = a\tan 2(x, y) \tag{7}$$

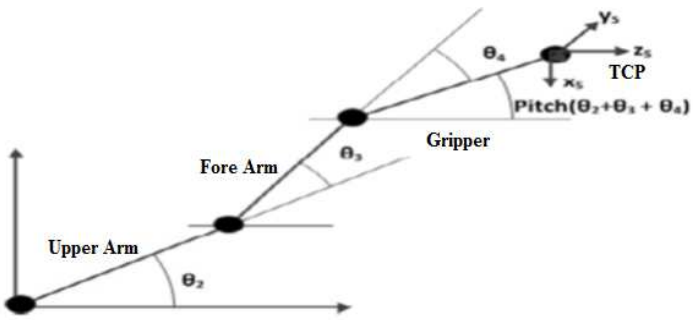

Figure 4: Showing the Pitch of SCORBOT ER-4u [4]

$$\theta_{234} = a\tan 2(r_{13}, \pm\sqrt{r_{23}^{\ 2} + r_{33}^{\ 2}}) \tag{8}$$

Here, atan2 is used because its range is [−π, π], where the range of atan is [−π /2, π /2].

Roll: The roll $\gamma = \theta_5$ is derived as follows

$$\theta_5 = a\tan 2(r_{12}/C_{234}, r_{11}/C_{234}) \tag{9}$$

Yaw: The yaw (α) of the Scorbot arm is defined by the base rotation i.e θ_1

From the above expression it can be seen that θ_2, θ_3 and θ_4 are merged in θ_{234}. In order to calculate them, it has to be decomposed. The following geometric solution method is used to estimate θ_2, θ_3 and θ_4.

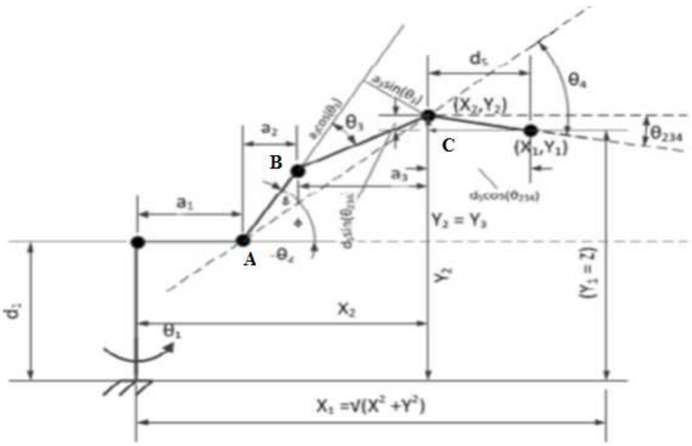

Figure 5: Geometric representation of SCORBOT [4]

From the above representation (Figure 5) [4] [17], the following relations were derived.

$X_1 = \sqrt{(X^2 + Y^2}$ and $Y_1 = Z$

As the Pitch $Pitch\ \beta = \theta_{234}$, Coordinates X_2 and Y_2 is found by following geometric relation

$X_2 = X_1 - d_5 Cos_{234}$ and $Y_2 = Y_1 + d_5 \sin\theta_{234}$

Similarly, the coordinates for X_3 and Y_3 is found as follows

$X_3 = X_2 - a_1$ and $Y_3 = Y_2$

When the law of cosine is applied to Δ ABC, θ_3 is obtained as

$$\cos\theta_3 = \frac{(X_3^2 + Y_3^2 - a_2^2 - a_3^2)}{2a_2a_3}$$

$$\theta_3 = a\tan 2(\pm\sqrt{1-\cos^2\theta_3}, \cos\theta_3) \qquad (10)$$

And from figure 7, $\theta_2 = -\phi - \delta$

$$\theta_2 = -a\tan 2(Y_3, X_3) - a\tan 2(a_3\sin\theta_3, a_2 + \cos\theta_3) \qquad (11)$$

Since $\theta_4 = \theta_{234} - \theta_2 - \theta_3$ (12)

Matlab program was written for calculating the forward and inverse kinematics developed in above sections of Scorbot ER 4u.

EXPERIMENTATION

In order to validate the kinematic model, measurements in terms of position and orientation, must be taken of the end effector. For the development of the programs considered here, only the position of the end effector was taken into

account.The experimental measurements were carried by mounting the robot on a plane white board as shown in figure 6.

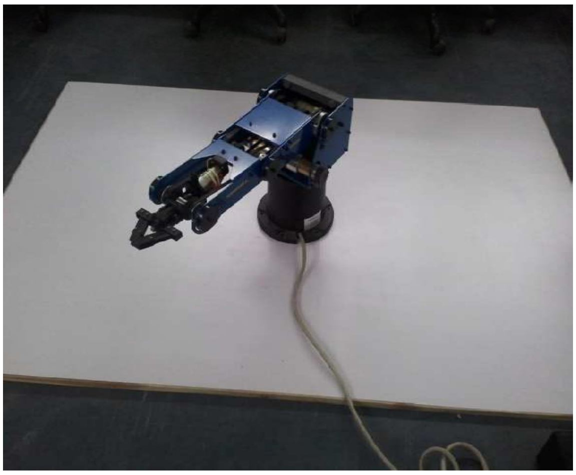

Figure 6: Experimental Setup Board

The workspace was divided into four quadrants. Different positions from each quadrant were selected so as to cover all workspace of the manipulator arm and the same are validated. The joint angles required to these reference positions were calculated using the developed inverse kinematic model in the previous section. The calculated joint angles were provided to robot control software and the resulting position of wrist in the Cartesian space was measured as shown in figure 7.

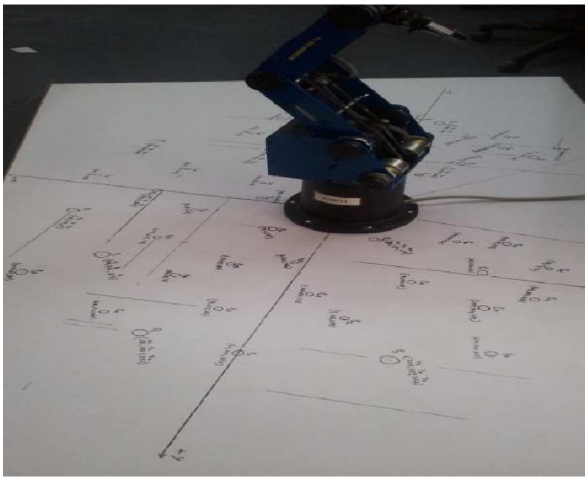

Figure 7: Cartesian Position Measurements

The reference positions, the calculated joints angles and the measured positions are tabulated in table 2 provided in appendix.

The results of the Cartesian error obtained are shown in the figure 8 (a-c).

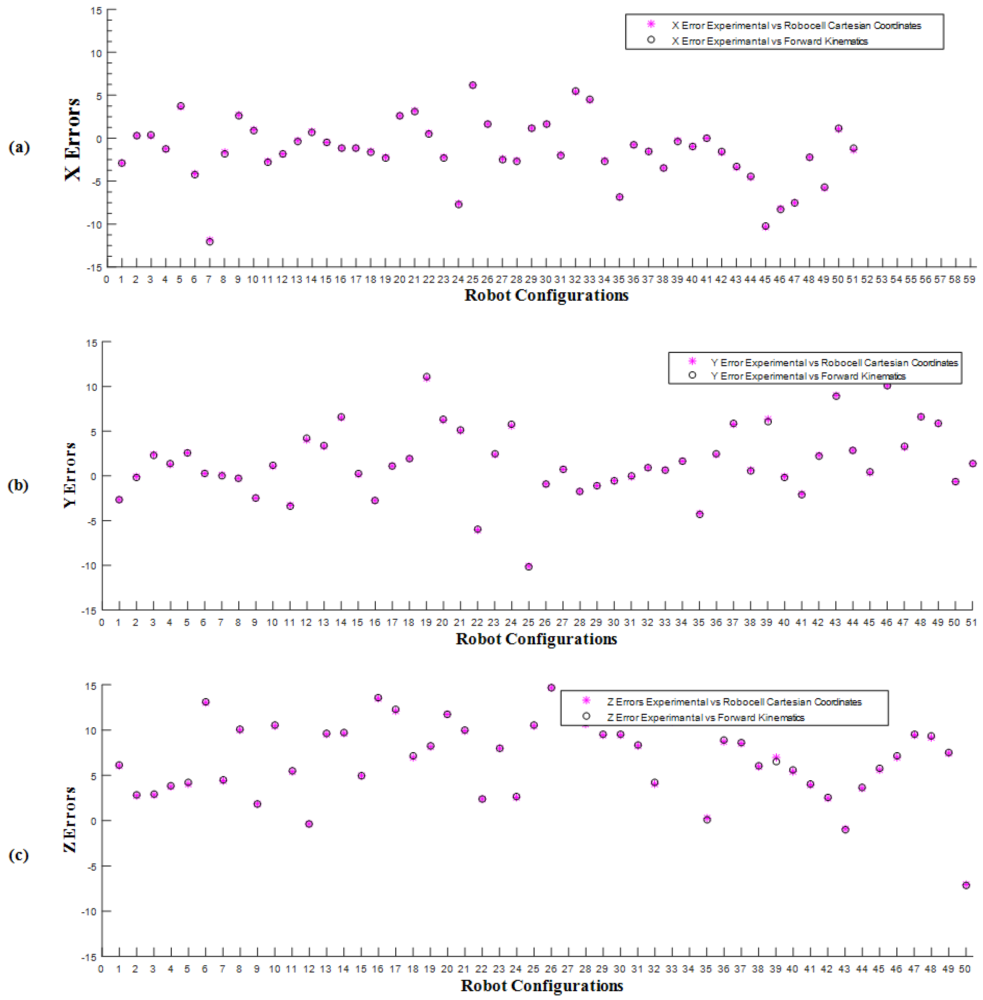

Figure 8: Absolute Percentage Error in Cartesian Coordinates (a) X-direction (b) (a) Y-direction (c) (a) Z-direction

The maximum percentage error found in X, Y and Z coordinates was 7.03, 7.84 and 14.92, respectively. Whereas, the minimum percentage error found in X, Y and Z coordinates was 0, 0 and 0.02, respectively. The average percentage error in X, Y and Z coordinates was 1.7, 1.38 and 3.36, respectively. Thus, the negligible values of average percentage error between the reference Cartesian positions and measured Cartesian positions validate the kinematic model of the articulated SCORBOT ER 4u robot manipulator.

CONCLUSIONS

Kinematic modeling of a robot is important for developing position control algorithms for the robot. In the present work, forward and inverse kinematic models were developed for Scorbot ER 4u robot manipulator and validated experimentally. For this purpose, reference coordinates in Cartesian space were taken distributed in the four quadrants in X-Y plane. The joint angles for the reference coordinates were calculated using the Inverse Kinematic model. The joint angles so obtained were provided as input to the robot controller in the experiments, and the resulting positions were measured. The negligible values of average percentage error between the reference and measured wrist positions in Cartesian space validate the kinematic model of the articulated SCORBOT ER 4u robot manipulator.

APPENDIX - I

Table 2: Results of Inverse Kinematics

Reference Cartesian Coordinate (mm)			Joint Angles by IK (BSEPR in degrees)					Measured Cartesian Coordinate (mm)			Absolute Percentage Error		
X	Y	Z	Theta1	Theta2	Theta3	Theta4	Theta5	X	Y	Z	X	Y	Z
334	325	337	44.2	-40.09	48.03	55.61	0	336	326.69	330.86	0.60	0.52	1.86
156	582.5	352	75.04	-0.03	0.03	-0.02	0	155.7	582.68	349.17	0.19	0.03	0.81
-206	569	352	110.01	-0.01	0.02	-0.03	-0.03	-206.4	566.72	349.05	0.19	0.40	0.85
-80	124	110	122.69	-32.53	131.34	0.2	-0.03	-78.7	122.67	106.11	1.65	1.08	3.67
-513	65	68	173.11	25.26	-2.01	22.32	0.11	-516.8	62.44	63.82	0.74	4.10	6.55
468	144	16	16.93	26.01	10.37	9.47	0.11	472.2	143.75	16.87	0.89	0.17	5.16
370	0	575	0	-90.02	89.92	0.04	0.11	382	0	570.54	3.14	0.00	0.78
500	-290	260	-30	26.77	-26.85	0.02	0.11	501.8	-289.72	249.92	0.36	0.10	4.03
248	-295	130	-50.01	0	90.07	-90.14	0.11	245.4	-292.56	128.18	1.06	0.83	1.42
116	-503	60	-77.14	17.55	19.87	0.22	0.15	115.1	-504.18	59.44	0.78	0.23	0.94
-21	-138	48	-98.55	-6.47	96.68	42.63	0.15	-20.2	-134.59	46.49	3.96	2.53	3.25
-73	-226	860	-107.18	-89.48	37	-0.02	-0.1	-71.2	-230.2	860.41	2.53	1.82	0.05
-306	-463	156	-123.58	4.86	24.01	3.29	0.08	-305.6	-460.38	146.32	0.13	0.57	6.62
-44	-581	264	-94.35	14.14	-15.17	18.96	0.04	-44.7	-587.65	254.31	1.57	1.13	3.81
-199	-519	246	-110.92	22.54	-0.07	-47.41	0.04	-198.5	-519.28	241.01	0.25	0.05	2.07
-268	-394	28	-124.3	16.66	19.68	25.79	0	-266.9	-391.23	26.39	0.41	0.71	6.10
-140	-317	306	-113.58	-67.33	103.65	25.81	0	-138.8	-318.1	293.74	0.86	0.35	4.17
-200	-437	120	-114.32	-5.99	42.32	25.81	0	-198.4	-438.91	112.83	0.81	0.44	6.35
-115	-499	514	-102.46	1.6	-52.11	53.54	0.04	-112.7	-510.08	505.71	2.04	2.17	1.64
-394	-448	361	-131.12	-0.01	-0.02	-0.01	0.04	-396.6	-454.35	349.26	0.66	1.40	3.36
0	-598	359	-90.01	0.02	-0.05	0.04	0	-0.1	-603.12	349.01	0.00	0.85	2.86
-47	-406	144	-96.77	1.85	82.39	-92.01	0.08	-47.5	-400.05	141.6	1.05	1.49	1.69
299	-520	357	-60.03	0.02	-0.04	0.03	0	301.3	-522.48	348.97	0.76	0.47	2.30
193	-325	573	-60.03	-90.08	90.03	-0.01	0	190.7	-330.76	570.34	1.21	1.74	0.47
101	-216	47	-65.26	-14.04	93.86	27.36	0	94.8	-205.79	46.44	6.54	4.96	1.21
327	-401	110	-50.88	28.13	-22.75	48.86	0	325.4	-400.12	106.32	0.49	0.22	3.46
515	-50	188	-5.6	7.7	-3.26	59.12	0	517.5	-50.74	172.34	0.48	1.46	9.09
365	-136	329	-20.06	-60.13	84.87	38.82	0	367.7	-134.25	318.21	0.73	1.30	3.39
194	-95	210	-25.96	-62.24	126.47	26	0	192.8	-93.87	200.42	0.62	1.20	4.78
175	-13	263	-4.1	-85.33	135.9	39.65	0	173.4	-12.43	253.44	0.92	4.59	3.77
38	-364	275	-83.73	-60.6	110.43	-2.91	0	40	-363.98	266.67	5.00	0.01	3.12
266	80	168	16.88	-39.82	133.07	-63.31	0	286.1	86.81	197.45	7.03	7.84	14.92
279	225	108	39.26	-23.34	80.3	27.06	0	274.5	224.36	106.96	1.64	0.29	0.97
78	475	231	80.33	25.37	-50.61	88.8	0	80.7	473.38	218.6	3.35	0.34	5.67
118	305	786	68.02	-65.66	-1.77	54.92	0	124.9	309.34	785.87	5.52	1.40	0.02
99	128	197	51.54	-65.66	147.3	-0.01	0	99.7	125.55	188.13	0.70	1.95	4.71
21	264	146	85.01	-41.26	116.61	6.28	0	22.5	258.17	137.35	6.67	2.26	6.30
423	427	355	45	0	0	0.01	0	426.5	426.47	348.97	0.82	0.12	1.73
186	373	176	63.07	-30.99	95.35	-23.97	0	186.4	366.98	169.51	0.21	1.64	3.83
236	532	332	66	-17.18	31.07	0	0	236.9	532.19	326.39	0.38	0.04	1.72
0	601	353	90	0	0	0.01	0	0	603.12	348.97	0.00	0.35	1.15
-111	450	289	103.73	-34.36	92.26	-57.88	0	-109.4	447.83	286.47	1.46	0.48	0.88
-299	360	499	130.11	-51.51	81.71	-68.11	180.07	-295.7	351.09	499.98	1.12	2.54	0.20
-368	301	268	140.64	-28.23	87.08	-58.84	177.38	-363.5	298.17	264.38	1.24	0.95	1.37
-375	171	130	154.94	-20.5	92.84	-33.22	180.08	-364.7	170.55	124.24	2.82	0.26	4.64
-179	292	107	121.2	-25.34	103.91	-17.44	180.08	-170.7	281.93	99.88	4.86	3.57	7.13
-295	87	233	163.76	-61.54	122.27	0.4	180.08	-287.5	83.74	223.42	2.61	3.89	4.29
-38	382	173	95.45	-36.52	96.65	-0.51	180.08	-35.8	375.36	163.68	6.15	1.77	5.69
-277	222	169	141.45	-39.74	103.91	-0.62	0	-271.3	216.17	161.43	2.10	2.70	4.69
-214	100	860	154.93	-87.48	29.52	8.65	0	-215.2	100.67	867.16	0.56	0.67	0.83
-333	505	353	123.38	0	0	0.01	0	-331.8	503.63	348.97	0.36	0.27	1.15
Average Absolute Percentage Error											**1.77**	**1.38**	**3.36**

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